ABSTRACT

Environmental pollution from heavy metals is an escalating global concern, posing a severe threat to the sustainability of ecosystems and human health. With the rise of industrialization, urbanization, and the indiscriminate use of agrochemicals, the discharge of toxic heavy metals into the environment has become alarmingly frequent and widespread. These pollutants enter terrestrial and aquatic environments through multiple anthropogenic routes industrial effluents, mining activities, fossil fuel combustion, wastewater irrigation, atmospheric deposition, and improper disposal of hazardous waste. Due to their non-biodegradable and persistent nature, heavy metals accumulate in soil, water, and biological organisms over time, exerting long-term ecological and physiological consequences. The present study focuses on the environmental impact of heavy metal pollution in freshwater ecosystems, with a particular emphasis on the bioaccumulation of toxic metals in economically and nutritionally important fish species. Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), arsenic (As), nickel (Ni), copper (Cu), and zinc (Zn) are particularly concerning due to their toxicity, mobility, and tendency to bioaccumulate and biomagnify through the food chain. While trace amounts of elements like copper and zinc are essential for enzymatic and metabolic functions, their elevated concentrations, as well as even minimal levels of non-essential metals like mercury, lead, and cadmium, can result in serious biochemical disruptions, genotoxicity, and tissue damage. This investigation explores the ecological pathways and biological impact of heavy metals in freshwater habitats and their consequences for aquatic organisms, particularly fish. Fish serve as effective bioindicators due to their physiological sensitivity to environmental changes and their position in the aquatic trophic structure. Metals infiltrate fish bodies mainly through

three pathways: (1) direct absorption across the gill epithelium from contaminated water, (2) ingestion of tainted food and sediments via the digestive tract, and (3) dermal exposure through the skin. Among these, gill absorption remains the dominant route, owing to the continuous contact between gill surfaces and the surrounding water. The experimental part of this study was conducted using *Labeo rohita*, *Catla catla*, and *Cirrhinus mrigala*, three common Indian major carps widely consumed across India. A total of 20 fish samples were collected from aquaria in Paschim Medinipur, West Bengal. The fish tissues—gills, liver, and muscles were dissected, oven-dried, and subjected to acid digestion using a mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$). Quantitative analysis of metal concentrations was carried out using Atomic Absorption Spectrophotometry (AAS), a sensitive and reliable analytical technique for trace metal detection. The data were statistically analyzed using SPSS Version 23, applying one-way ANOVA and independent t-tests to evaluate differences in metal concentrations among species and tissues, with significance determined at $p < 0.05$. The results indicated that heavy metal accumulation was highest in liver tissues, followed by gills, and lowest in muscles. The liver's high metal content can be attributed to its central role in detoxification and metal sequestration. Zinc and lead emerged as the most prevalent metals in all fish species, followed by chromium, cadmium, and nickel. Variations in accumulation patterns among fish species suggest the influence of ecological and behavioral factors, including feeding habits, metabolic rates, and trophic positioning. Notably, species that are higher in the trophic hierarchy exhibited greater levels of bioaccumulation, confirming the occurrence of biomagnification in the aquatic food web. Physicochemical factors of water such as temperature, pH, dissolved oxygen (DO), and conductivity were also found to significantly influence metal uptake in fish. Seasonal variations, water renewal rates, and sediment chemistry contribute to fluctuating metal concentrations, thereby affecting metal bioavailability and absorption efficiency. Biological factors, including fish age, body weight,

sex, and reproductive stage, further modulate metal retention and toxicity levels. The implications of heavy metal accumulation extend beyond fish health. These metals disrupt enzymatic systems, alter hematological parameters, impair reproduction, and lead to oxidative stress, immune suppression, and behavioral abnormalities in fish. On an ecosystem scale, heavy metal contamination reduces aquatic biodiversity, alters plankton and microbial communities, and destabilizes predator-prey dynamics. Through bioaccumulation and subsequent biomagnification, metals traverse through food chains and pose risks to higher organisms including birds, mammals, and humans. Fish muscle tissue, though exhibiting the lowest concentration of metals compared to liver and gills, remains the most relevant from a public health perspective, as it constitutes the primary edible portion. The chronic ingestion of fish contaminated with heavy metals such as arsenic, cadmium, and lead can lead to serious health effects in humans—ranging from nephrotoxicity, hepatotoxicity, and neurotoxicity to carcinogenesis, cardiovascular disorders, and developmental defects. This is particularly concerning for vulnerable populations, including children and pregnant women, whose physiological systems are more sensitive to toxic insults. Heavy metal contamination also affects the agricultural sector. The application of metal-contaminated compost, sludge, or irrigation water leads to the accumulation of toxic elements in agricultural soils. Plants absorb these metals through their roots, which then enter the food chain. Consequently, heavy metals infiltrate dietary vegetables and cereals consumed by humans. Compostable organic wastes such as municipal solid waste, sewage sludge, and animal manure often contain residual metals that interfere with microbial activity, hindering natural composting and vermicomposting processes. Such agricultural practices, if unregulated, contribute to long-term soil degradation and reduced crop productivity. The heavy metal can come to the natural environment by various routes such as environmental weathering, use of synthetic fertilizers and pesticides, and anthropogenic discharges. Bioaccumulation occurs in primary producers

and aquatic organisms such as fish, which are then consumed by secondary and tertiary consumers, thereby leading to biomagnification. This phenomenon has profound implications for food safety and public health. The health risks associated with metals like arsenic, cadmium, lead, and mercury are well-documented—they are linked to neurological damage, endocrine disruption, organ failure, reproductive abnormalities, and various forms of cancer. Their persistent and non-degradable nature makes them particularly hazardous in both urban and rural environments. In West Bengal, the challenge of heavy metal toxicity is further intensified due to the combination of densely populated regions, rapid urban growth, and industrial clusters situated near freshwater sources. Poor enforcement of environmental regulations, lack of infrastructure for proper effluent treatment, and inadequate monitoring systems exacerbate the problem. Fish farming, an economically vital activity in the region, is directly affected by declining water quality and toxic metal load in water bodies, thereby jeopardizing food security, livelihoods, and public health. To combat this multifaceted crisis, an integrated and proactive approach is essential. Environmental monitoring programs must be strengthened, with regular testing of water, soil, and biological samples for metal concentrations. All effluents from industrial, municipal, and agricultural sources should undergo stringent treatment before discharge into natural water bodies. Advanced technologies such as membrane filtration, ion exchange, and electrochemical treatments should be employed for metal removal. Bioremediation and phytoremediation offer sustainable and cost-effective solutions. These methods employ metal-tolerant microbes, fungi, algae, and hyperaccumulator plants to extract, stabilize, or transform heavy metals into less toxic forms. For instance, aquatic macrophytes like *Eichhornia crassipes* (water hyacinth) and terrestrial plants like *Brassica juncea* (Indian mustard) have demonstrated high metal uptake capacities. Implementing such green technologies in contaminated zones can significantly reduce metal concentrations in soil and water without introducing secondary

pollutants. At the policy level, guidelines issued by institutions such as the Central Pollution Control Board (CPCB) in India must be strictly implemented. These include permissible limits for metal concentrations in water, soil, and food products, and protocols for the disposal of industrial and municipal waste. The CPCB's framework should be used not just as a regulatory tool but also as a strategic guideline to promote best practices in pollution control, waste management, and environmental conservation. Public awareness and education are equally critical in addressing the problem of heavy metal pollution. Local communities, farmers, and aquaculture practitioners need to be informed about the sources and risks associated with heavy metals and trained in preventive measures. Campaigns emphasizing safe agricultural practices, judicious use of fertilizers and pesticides, proper composting methods, and responsible fish farming can build resilience at the grassroots level. In conclusion, heavy metal pollution represents a silent yet potent threat to ecological balance, food security, and public health. Its persistence in the environment, its ability to bioaccumulate and biomagnify, and its chronic toxicological impacts demand urgent scientific, regulatory, and community-level action. This study reinforces the value of freshwater fish as reliable bioindicators of environmental contamination and underlines the urgent need for comprehensive mitigation strategies. Addressing this challenge requires a multipronged effort: scientific innovation in pollution monitoring and remediation, strict enforcement of environmental regulations, stakeholder education, and inclusive policymaking. Only through coordinated action at local, regional, and global levels can we protect ecosystems, safeguard human health, and secure a sustainable future against the growing menace of heavy metal toxicity.